TECHNICAL MEMORANDUM

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| TO: | KEVIN CLARKE, NYCDEP | DATE: | AUGUST 16, 2013 |
| FROM: | THOMAS NEWMAN<br>STEVE ERTMAN<br>MASA TAKAMATSU | RE: | IMPACT OF REACTIVATING THE GOWANUS CANAL FLUSHING TUNNEL ON CANAL BED SEDIMENT EROSION, TRANSPORT, AND DEPOSITION |
| CC: | EILEEN MAHONEY, NYCDEP | FILE: | 337.194031.001 |

## EXECUTIVE SUMMARY


The nearly completed renovation of the Gowanus Canal Flushing Tunnel system will increase maximum discharge rates by 40 percent versus the pre-renovation condition. The purpose of this investigation was to estimate the impact of reactivating the renovated Flushing Tunnel on the sediment bed of Gowanus Canal. Bathymetric surveys indicate that sediment levels near the Flushing Tunnel outlet have increased significantly over the past several years, particularly since the tunnel has been inactive during renovation.

Results of a computational fluid dynamics (CFD) modeling analysis, together with available bathymetry and grain-size characteristics of the sediments in the area, indicate that reactivation of the renovated Flushing Tunnel could scour approximately 27,000 $ft^3$ of Gowanus Canal sediments from a 6,500 $ft^2$ area in the vicinity of the tunnel outlet (Figure 12). The scoured sediments will be transported and deposited downstream. Depositional behavior is complex, particularly for fine, cohesive sediments such as those in Gowanus Canal. However, a sediment-transport assessment treating the scoured sediment as non-cohesive indicates that about 53 percent of the scoured mass would deposit in the upper Gowanus Canal (within 2,500 ft of the canal head). A subjective assessment treating the scoured mass as cohesive indicates that perhaps 70 percent of the scoured mass would deposit within the same region. In either case, it is expected that some fraction of the finest grain-size material (up to perhaps 10 percent of the scoured mass) may transport as suspended load downstream as far as Gowanus Bay.



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## INTRODUCTION

The Flushing Tunnel was designed to provide a constant influx of water to the head of Gowanus Canal to provide dissolved oxygen to the canal and to promote hydraulic flushing and to maintain higher water quality in the canal. The brick, 12-ft-diameter, brick, Flushing Tunnel runs approximately 6,070 linear feet from Buttermilk Channel to the head of Gowanus Canal . (NYCDEP 2005) (Figure 1). Downstream of the tunnel pumping facilities—located near the head of Gowanus Canal—the Flushing Tunnel expands to a diameter of 12.5 ft and it gradually expands further to an oblong opening 50-ft wide by 12.5-ft high at its discharge into the canal at the end of Douglass Street (Figure 2).

From March 1999 to July 2010, the Flushing Tunnel system operated at an average discharge rate of about 154 million gallons per day (MGD). The system was highly susceptible to tidal conditions, with field measurements showing a peak discharge rate of 195 MGD at high tide, and zero discharge at minimum low tide, when the system was unable to function (NYCDEP, 2008). As part of DEP's Gowanus Facilities Upgrade project, the Flushing Tunnel was deactivated in July 2010 (HydroQual, 2011) in order to modernize the system to increase the Flushing Tunnel pumping capacity and reduce downtime. Once renovations are completed later in 2013, the average pumping capacity of the system is expected to increase 40 percent to 215 MGD, the high-tide peak capacity is expected to increase to 252 MGD, and the low-tide minimum capacity is expected to increase to 175 MGD.

Table 1 summarizes the discharge characteristics of the Flushing Tunnel for both the pre- and post-renovation conditions. Figure 3 illustrates the expected post-renovation variation of pumping capacity over the tidal cycle.

**Table 1. Flushing Tunnel Pumping Capacity, Pre- and Post-Renovation**

| Pumping Capacity (MGD) | Average (MGD) | Maximum[1] (MGD) | Minimum[2] (MGD) |
|---|---|---|---|
| Pre-Renovation | 154 | 195 | 0 |
| Post-Renovation | 215 | 252 | 175 |

[1] Approximate at High Tide
[2] Approximate at Low Tide

During the period that the Flushing Tunnel was inactivate, sedimentation continued to occur in some areas of the canal, particularly in the immediate vicinity of the Flushing Tunnel discharge, where three or more feet of sedimentation built up between 2009 and 2011.

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## PURPOSE OF INVESTIGATION

The purpose of this investigation was to evaluate how reactivating the Flushing Tunnel after renovation will affect the distribution of sediments within the canal. It is anticipated that reactivating the Flushing Tunnel will cause a scour furrow to redevelop along the canal bed in the vicinity of the discharge and, given the 30 percent increase in the Flushing Tunnel's maximum discharge rate, the scour furrow may be larger than it was prior to renovation. To predict the volume (scour depth and horizontal extent) of sediment that would likely erode under the renovated Flushing Tunnel discharge, this investigation pursued several lines of investigation, including:

- Evaluation of multi-year bathymetric data to assess historical characteristics of the Flushing Tunnel scour furrow and to assess historical erosion and deposition patterns in upper Gowanus Canal,

- Analysis of data from sediment cores collected near the head of Gowanus Canal to assess sediment erosion and transport potential,

- Development of a computational fluid dynamic model (CFD) of the renovated Flushing Tunnel turbulent jet to determine the fluid shear stress that would be exerted on the sediment bed and to simulate the likely extent of sediment scour, and

- Application of sediment-transport theory to provide a screening-level assessment of expected patterns of sediment erosion, transport, and deposition due to activation of the renovated Flushing Tunnel.

## BATHYMETRIC EVALUATION

Gowanus Canal bathymetry data are available from surveys conducted in 2003, 2009, and 2011. The 2011 data were collected prior to the deactivation of the Flushing Tunnel in July 2010 for construction associated with the renovation process.

The invert of the Flushing Tunnel outlet in Gowanus Canal lies about one-half foot above the native sediment surface, which is located at elevation -18 ft NAVD88 (Figure 4). Over time, some 12 ft of sediment has deposited in the vicinity of the Flushing Tunnel outlet at the head of Gowanus Canal, such that the invert of the Flushing Tunnel outlet is now well below the adjacent sediment surface.

In anticipation of activating the Flushing Tunnel in March 1999, NYCDEP dredged the immediate vicinity of the Flushing Tunnel outlet in August/September 1998 (NYCDEP 1999). This dredging removed about 2,000 cubic yards of material to "ramp" sediment levels from the canal down toward the Flushing Tunnel invert at its outlet. As shown on Figure 4, subsequent bathymetry surveys in

2003, 2009 and 2011 show that sediment levels along the eastern half of the canal across from the Flushing Tunnel outlet remained relatively stable, but sediment levels in the dredged area closer to the outlet increased over time, particularly between the 2009 and 2011 surveys, which encompassed the period that the Flushing Tunnel was deactivated for renovation. Beyond the vicinity of the Flushing Tunnel—between Union and 3rd St.—bathymetry changes have been generally less pronounced, with deposition in some areas and erosion in other areas (HDR|HydroQual, 2011).

When the renovated Flushing Tunnel is reactivated, the action of the discharge is expected to erode sediments that have deposited near the tunnel outlet and, given the 40 percent increase in maximum discharge rates from the pre-renovation period, the size of the scour furrow may become larger than what was observed in the pre-renovation period (1999-2010).

Figure 5 presents the bathymetry along the centerline transect of the upper 700 ft of the canal, as interpolated from the 2003, 2009 and 2011 surveys. As annotated on Figure 5, the sediment-bed level along the first 200 ft (upstream of the Flushing Tunnel) is elevated relative to the next 300 ft (downstream of the Flushing Tunnel). This "step" in sediment levels may be explained by the increase in flow from the upper section to the downstream section. Bed levels for 2009 and 2011 are similar, suggesting that a state of quasi-equilibrium was achieved. The bathymetric data suggest that this section of the upper Gowanus Canal is primarily a transportation corridor for sediment introduced at the head of the canal. Periodic CSO high-flow events, combined with discharge from the Flushing Tunnel (when operational), produce an approximate net balance between sediment deposition and sediment erosion over time. Beyond 500 ft from the canal head, the bathymetric profiles show the bed dropping off rather abruptly to a minimum depression elevation near Sackett Street. Up to 6.5 ft of sediment deposited in this depression between 2003 and 2011, and a comparison of the 2003, 2009, and 2011 bathymetric profiles show a downstream prograding deposition front (an "advancing shelf") at the upstream edge of the depression.

A reasonable interpretation of the multi-year, centerline bathymetric profiles (Figure 6) is that coarser sediment deposited at the mouth of CSO RH-034 is periodically eroded by high-flow CSO events, is transported downstream primarily as bed load, and is deposited in the Sackett Street depression, where the sudden drop off in bed elevation results in an abrupt decrease in cross-sectional average velocity and a corresponding decrease in bed shear stress. In 2011, the Sackett Street depression remained approximately 2-ft deeper than the bed elevation just upstream, suggesting that the depression might retain additional depositional capacity. The bathymetric evaluation is relevant to reactivation of the renovated Flushing Tunnel, because the basic patterns of sediment erosion, transport, and deposition in upper Gowanus Canal are expected to remain consistent as the reactivated turbulent jet erodes a new scour furrow at the tunnel outlet.

## SEDIMENT CHARACTERISTICS

Physical characterization of the sediment bed (i.e., grain-size distribution, cohesiveness, critical bed shear stress for erosion) near the Flushing Tunnel outlet is a prerequisite to any assessment of sediment transport potential. Sediment physical properties for upper Gowanus Canal were derived from three data sources: sediment-core sampling (USACE 2003), bed surface Sedflume testing (Sea Engineering 2011), and wet-weather CSO sampling (NYCDEP 2013).

Sediment grain-size distributions were available from 5 stations (USACE: GC-03-28, -29, -30; Sea Engineering: SF-1, -2) located within 1,000 ft of the head of Gowanus Canal (Figure 6). However, USACE cores GC-03-29 and GC-03-30 were omitted from analysis because their sampling intervals within the sediment were too deep (18.5–20 ft and 8.0–9.5 ft below sediment surface, respectively). USACE core GC-03-28, with a sampling interval of 2.5–4.0 ft below sediment surface, was retained for analysis. The two surficial (0–19 cm below sediment surface) cores collected by Sea Engineering (SF-1, SF-2) were also retained. As shown on Figure 6, Stations SF-1 and SF-2 were closely adjacent and their grain-size distributions were very similar, so data for these two stations were combined as a mean grain-size distribution ("Sedflume Average"). For comparison, a grain-size distribution for CSO solids from RH-034 (NYCDEP 2013) is also shown on Figure 6. A composite grain-size distribution was derived from these three sources to represent surficial sediment in upper Gowanus Canal (Figure 6 and Table 2).

**Table 2. Grain Size Distribution[‡] by Mass for Gowanus Canal Sediments**

| | |
|---|---|
| Medium Sand (250 – 400 μm) | 5% |
| Fine Sand (125 – 250 μm) | 9% |
| Very Fine Sand (62 - 125 μm) | 14% |
| Coarse Silt (31 - 62 μm) | 15% |
| Medium Silt (16 - 31 μm) | 16% |
| Fine Silt (8 - 16 μm) | 14% |
| Very Fine Silt (4 - 8 μm) | 14% |
| Clay (< 4 μm) | 13% |

‡ Wentworth Scale

More than 70 percent (by mass) of the derived composite sediment are "fines" with nominal grain-size diameters ≤ 62-μm, indicating that sediments in upper Gowanus Canal are cohesive. Sediment transport of cohesive sediments is difficult to predict *a priori*, because the cohesive strength of the bed is typically site specific and can vary by orders of magnitude between and even within locales. The best approach for assessing the stability of a cohesive bed is to measure the critical bed shear stress for erosion and the sediment erosion rate directly with a controlled-flow device such as the Sedflume (McNeil *et al*. 1996, Roberts *et al*. 1998). Sedflume test results (Sea Engineering 2011) for surficial sediments (0–19 cm below sediment surface) were available at stations SF-1 and SF-2. Critical bed shear stress for erosion varied by a factor of 2–3 with depth in the sediment (Figure 7). Although stations SF-1 and SF-2 were closely adjacent (Figure 6, upper panel), their vertical profiles of critical bed shear stress differed appreciably. Buried leaves, roots, and pieces of wood contributed to the variability (Sea Engineering 2011). Erosion rates for SF1 and SF2 were more consistent and provided a suitable regression relationship ($R^2$ = 0.94) between erosion rate and bed shear stress (Figure 8) once erosion was initiated.

## CFD MODELING

The Flushing Tunnel enters Gowanus Canal as a submerged, three-dimensional, turbulent jet that expands radially with distance from the tunnel outlet, projecting a cone of high-velocity fluid into the ambient water of Gowanus Canal. As the outer envelope of the jet intercepts the sediment bed, a turbulent boundary layer develops. At the point of interception, the boundary layer is exceedingly thin, generating intense vertical velocity shear near the bed, as well as intense tangential force (i.e., bed shear stress) on the bed surface. With increasing distance from the tunnel outlet, the radial expansion of the jet decreases the areal-averaged cross-sectional velocity, but the higher-velocity jet core begins to impinge on the bed. Coincidently, the developing turbulent boundary layer grows thicker as turbulent kinetic energy mixes away from the bed, resulting (in a relative local sense) in a decrease in bed shear stress. The complexity of these dynamic fluid processes cannot be simulated by typical hydrodynamic models, which do not include all of the relevant physics nor the fine spatiotemporal resolution needed to perform meaningful calculations. Instead, a high-resolution computational fluid dynamic (CFD) model of the Flushing Tunnel discharge into Gowanus Canal was developed using ANSYS Fluent (version 6.3.26). The objective of the CFD modeling was to compute near-field values of bed shear stress as the Flushing Tunnel turbulent jet intercepts the sediment bed.

The model domain included the head of Gowanus Canal, including the four-barrel outfall structure for CSO RH-034. To ensure that the Flushing Tunnel turbulent jet was properly developed before entering Gowanus Canal, the model included 90 ft of the funnel-shaped tunnel upstream of the outlet. The model was meshed using tetrahedral cells with 0.7-ft spacing. A model restriction on the number of computational mesh cells limited the canal portion to 270 ft from the canal head, given the canal width of 100 ft (Figure 9). Model bed elevations were derived from bathymetric data. To represent more of the canal, a second model was developed to represent the next 300-ft downstream (by 100-ft wide) portion of Gowanus Canal. Outflow boundary conditions from the upstream mesh provided inflow boundary conditions to the downstream mesh, effectively doubling the model length for upper Gowanus Canal to 570 ft from the canal head.

## ***Calibration***

Model calibration was performed using 2003 Gowanus Canal bathymetry and the pre-renovation maximum tunnel discharge (195 MGD at high tide, 86 MGD low tide). High- and low-tide conditions were both examined, and it was determined that the higher-discharge high-tide condition generated the highest bed shear stress near the tunnel outlet. The calibration procedure assumed that the 2003 bathymetry represented the equilibrium scour condition for the pre-renovation Flushing Tunnel turbulent jet. Given an appropriate model geometry and tunnel discharge, the calibration process involved specifying a critical bed shear stress for erosion and adjusting bed roughness until the model-computed bed shear stress at the perimeter of the 2003 scour furrow was fractionally less than the specified critical bed shear stress for erosion.

Given the variability in Sedflume test results data for Gowanus Canal sampling stations SF-1 and SF-2 (Figure 7), specifying an appropriate critical bed shear stress for erosion becomes somewhat subjective. It should be noted, however, that the calibration process is self correcting because the specified critical bed shear stress for erosion and the calibration-adjusted bed roughness co-vary to produce a pattern of shear stress on the bed that matches the dimensions of the 2003 scour furrow. If the critical bed shear stress for erosion was specified too large (or too small), the calibration-adjusted bed roughness would decrease (or increase) proportionally until the pattern of model-computed bed shear stress matched the dimensions of the 2003 scour furrow. For each instance, the computed erosive potential of the Flushing Tunnel turbulent jet would be similar.

After careful consideration, a critical bed shear stress for erosion of 0.55 Pa was selected. This value was close to the median value measured by the Sedflume tests for stations SF-1 and SF-2. The value is also near the median value for a wide range of cohesive bed types (Whitehouse *et al.* 2000, Section 4.2). Given this critical bed shear stress for erosion, a calibration-adjusted bed roughness of 450 μm was found to produce the best match between model-computed bed shear stress and dimensions of the 2003 scour furrow (Figure 10), with the maximum bed shear stress along the steep perimeter of the scour furrows just slightly less than 0.55 Pa. The bed roughness value represents a combination of grain-size roughness and roughness from larger bed forms (e.g., small mounds, ripples, and pits).

## ***Prediction of Scour for Renovated Flushing Tunnel***

Model scour predictions for the renovated Flushing Tunnel were performed using the same basic model geometry described above, but using the 2011 bathymetry, in which the historical scour furrow at the tunnel outlet was largely filled with sediment (Figure 4). A critical bed shear stress for erosion of 0.55 Pa was again specified, and bed roughness was set to the calibration-adjusted value of 450 μm. Flushing Tunnel discharge was ramped up incrementally in five steps, from 75 MGD to the renovated Flushing Tunnel maximum high-tide discharge of 252 MGD, with the ramped increments representing an approximately linear increase in maximum bed shear stress.

For Flushing Tunnel discharge equal or greater than 100 MGD, model-computed bed shear stress in areas adjacent to the tunnel outlet exceeded 0.55 Pa, indicating that those areas would be eroded (i.e., "scoured"). Erosion was simulated by decreasing the bed elevation incrementally in areas computed to be erosive and re-running the model with the scoured bathymetry to re-assess bed shear stress. The procedure was repeated at each incremental discharge until bed elevation was sufficiently scoured such that bed shear stress no longer exceeded the critical bed shear stress for erosion. Based on the 2011 bathymetry, Table 3 presents the predicted cumulative sediment volume scoured at each discharge. An implied assumption here is that sediment volume scoured at a specified tunnel discharge will be similar whether the tunnel discharge was ramped up incrementally or set to the specified discharge instantaneously. The predicted total scour volume for the renovated Flushing Tunnel maximum discharge of 252 MGD was approximately 27,000 $ft^3$ from an area of about 6,500 $ft^2$. Figure 11 shows the model-predicted scoured bathymetry (depths relative to NAVD88) for the maximum tunnel discharge of 252 MGD. Figure 12 shows the corresponding predicted depths of scour relative to the 2011 bathymetry. Figure 13 presents the same scour volumes versus depth and also indicates the volumes scoured below the 2003 depth profile (e.g., the predicted volume scoured beyond the scour furrow that existed in 2003).

**Table 3. Predicted Scour Volume[1] for Different Flushing Tunnel Discharge Rates**

| Flow (MGD) | Volume (cf) |
|---|---|
| 75 | 0 |
| 100 | 1,540 |
| 153 | 6,249 |
| 192 | 9,777 |
| 224 | 16,226 |
| 252 | 26,814 |

[1] Beginning with 2011 bathymetry

## SEDIMENT TRANSPORT: A SCREENING-LEVEL ASSESSMENT

While the Flushing Tunnel CFD model provides useful predictions of bed shear stress, as well as the dimensions and volume of the predicted scour pit outside the tunnel outlet, it cannot predict the transport or deposition of scoured sediment downstream. Predicting the erosion, transport, and deposition of cohesive sediments is a difficult endeavor in any case. Non-cohesive sediments erode, transport, and deposit as discrete particles, and semi-empirical force-balance relationships for predicting and quantifying these processes are reasonably accurate. In contrast, cohesive beds typically erode by mass failure, when bed shear stress exceeds the cohesive strength of a section of the bed, and part of the bed surface peels away. Near-bed turbulent shear then breaks the eroded mass into smaller pieces, but is unlikely to disaggregate the eroded mass into the discrete "parent" particles described by a sediment-core grain-size distribution. Clay particles that do disaggregate may re-aggregate (i.e., flocculate) in regions of high suspended-sediment concentration. Sediment flocs settle more rapidly than their constituent particles and can envelop and strip even larger discrete particles or particle aggregates from the water column. Our ability to model these cohesive-sediment processes is limited, and typically requires extensive collection of field data and extended model-calibration efforts. Nevertheless, assessing sediment transport of cohesive sediments using semi-empirical relationships applicable to non-cohesive particles can provide useful insight, as long as it is recognized that the transport potential of the fine grain-size fractions ($\leq 63$ μm) is typically overestimated.

## *Estimating Bed Shear Stress*

Assessing the fate of sediments scoured by the renovated Gowanus Canal Flushing Tunnel requires knowledge of bed shear stress downstream, but the Flushing Tunnel CFD model only extends 570 ft from the head of the canal. To extend the assessment further downstream, a scaling approach—appropriate for a screening-level assessment—was used to estimate bed shear stress from the vicinity of the Flushing Tunnel to a position 2,450 ft from the canal head (e.g., the location of the first turning basin (at 4th Avenue).

Bed shear stress $(\tau_b)$ in Gowanus Canal can be related to the cross-sectional average velocity $(\overline{U})$ by a quadratic drag law of the form

$$\tau_b = \rho C_D \left(\overline{U}\right)^2 \tag{1}$$

where $\rho$ is water density, and $C_D$ is a drag coefficient that accounts for all types of open-channel flow resistance, including grain-size roughness, form drag, bulkhead roughness, and shape drag due to overall channel shape and shape variation. The magnitude of bed shear stress at some Point 2 relative to its value at another Point 1 is described by the ratio

$$\frac{\tau_{b2}}{\tau_{b1}} = \frac{\rho C_D \left(\overline{U_2}\right)^2}{\rho C_D \left(\overline{U_1}\right)^2} \tag{2}$$

If we assume that water density and the drag coefficient are reasonably constant in upper Gowanus Canal, then an unknown bed shear stress at Point 2 can be estimated from a known bed shear stress at Point 1 by

$$\tau_{b2} \approx \tau_{b1} \left(\overline{U_2}/\overline{U_1}\right)^2 \tag{3}$$

as long as $\overline{U_1}$ and $\overline{U_2}$ are also known. Bed shear stress is known within the domain of the Flushing Tunnel CFD model, and the cross-sectional average velocity at any point of interest in upper Gowanus Canal can be estimated by

$$\overline{U} = Q/A_x \tag{4}$$

where $Q$ is the Flushing Tunnel discharge, and $A_x$ is the Gowanus Canal wetted cross-sectional area at the point of interest. Thus, by determining $A_x$ along the canal, the bed shear stress downstream of the Flushing Tunnel can be estimated by scaling relative to a known bed shear stress in the domain of the CFD model. This technique ignores the effect of tidal currents, which tend to be rather weak in the upper canal.

Three parallel transects were established running from the head of Gowanus Canal to a point 2,450-ft downstream (Figure 14). Wetted cross-sectional area was calculated every 10 ft along the transects by measuring channel width from GIS data, determining bottom elevation from the 2011 bathymetric data (Figure 15), and assuming that water surface elevation was fixed at mean sea level. A reference bed shear stress of 0.3 Pa was selected near the downstream boundary of the CFD model, and cross-sectional average bed shear stress along the upper 2,450 ft of the Gowanus Canal was scaled relative to this reference value using Equations (3) and (4). The results are presented in Figure 16. The method assumes that discharge from the Flushing Tunnel is distributed relatively evenly across a canal cross section, so estimated values of bed shear stress adjacent and upstream of the Flushing Tunnel outlet (approximately 0-300 ft from the canal head) should be disregarded as invalid.

## ***Shields' Curve***

For non-cohesive sediments, the initiation of bed erosion can be predicted based on the Shields' Curve, which combines an empirical fit of the measured critical bed shear stress for erosion ("erosion threshold") with the force balance between gravity and fluid drag acting on particle of known density (typically set to the density of quartz sand, 2.65 g $cm^{-3}$) and diameter. Soulsby and Whitehouse (1997) extended Shields' Curve to finer grain sizes and determined an empirical fit to a wide variety of data (Figure 17, red curve). Eroded sediment may transport as bed load or as suspended load, depending on the magnitude of near-bed turbulent kinetic energy (which scales with the magnitude of bed shear stress). Particles moving in bed load roll, slide, and hop (i.e., saltate) along the bed, and bed load is the dominant mode of transport for slow flows and/or large sediment grains. For faster flows and/or smaller sediment grains, particles will be mixed upward from the bed by turbulence and will travel as suspended load. The transition between bed load and suspended load transport for a non-cohesive particle is typically defined when the particle gravitational fall velocity ($w_s$) equals the turbulent shear velocity ($u_*$). For simple boundary layer flow, the turbulent shear velocity is related to bed shear stress by $u_* = \sqrt{\tau_b/\rho}$. A curve demarking incipient suspension is included in Figure 17 as a dashed blue line, for which the particle gravitational fall velocity was calculated based on Cheng's (1997) equation for natural particles. A notable feature of Figure 17 is that the curve demarking incipient suspension intercepts Shield's Curve for the erosion threshold at a particle diameter of approximately 150 μm. What this indicates (and what has been validated through observation) is that when bed shear stress is at or slightly larger than the critical bed shear stress for erosion, non-cohesive particles > 150 μm tend first to move as bedload; whereas, when non-cohesive particles ≤ 150 μm erode, they tend to transport immediately as suspended load.

## ***Transport Assessment for Non-Cohesive Sediment***

Given estimates of bed shear stress in upper Gowanus Canal (Figure 16) and semi-empirical curves describing transport of non-cohesive sediment (Figure 17), a screening-level assessment of sediment transport for sediment scoured by the renovated Flushing Tunnel is now possible. It should be noted explicitly that this assessment will equate the critical bed shear stress for erosion with the critical bed shear stress for deposition, which is not strictly valid. Nevertheless, the two critical values should be reasonably close.

As shown in Figure 18, bed shear stress in upper Gowanus Canal can be characterized roughly by four values of bed shear stress (0.3, 0.2, 0.1, and 0.05 Pa), which are presented in the figure as color-coded horizontal lines.

- From the outlet of the Flushing Tunnel to a point approximately 500 ft from the canal head, the cross-sectional average bed shear stress is close to or exceeds 0.3 Pa. Examining the empirical curves in Figure 17, this bed shear stress is erosive for all sediment grain sizes observed in upper Gowanus Canal (≤ 400 μm, Table 2). Therefore, at the renovated Flushing Tunnel maximum discharge of 252 MGD, *all* sediment scoured by the turbulent jet would continue to transport through this section of the canal. Particles greater than about 190 μm would transport as bedload, but approximately 92% of the eroded sediment mass would transport through the water column as suspended load.

- At a point approximately 525 ft from the canal head, the cross-sectional average bed shear stress decreases abruptly, due to a corresponding increase in the wetted channel cross-sectional area at the Sackett Street depression. This abrupt drop in bed shear stress presents an opportunity for deposition. A bed shear stress of 0.2 Pa represents approximately the midpoint of the abrupt drop. At this bed shear stress, deposition would occur for non-cohesive sand with a diameter greater than about 350 μm (per Table 2 and Figure 6, about 3 percent of total scoured mass); sand with diameters between about 150–350 μm would transport as bed load; and some 90% of the eroded sediment mass would be transporting as suspended load.

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- Bed shear stress continues to drop to a value of near 0.1 Pa beginning at the Sacket Street depression (650 ft from the canal head) and continuing to about 1,100 ft. In that region, deposition would occur for particles sized more than 50 μm. Sands (≥ 62 μm, representing about 28% of the eroded sediment mass) would likely settle, but finer particles (coarse silts 50–62 μm, another 4% of the eroded sediment mass) may be transported beyond this region before settling. Some 68 percent of the total eroded mass would continue to transport downstream as suspended load.

- At about 1,200 ft from the canal head, cross-sectional average bed shear stress decreases to a characteristic value of 0.05 Pa and remains close to this value through the end of the assessment section at 2,450 ft from the canal head. Through this canal section, deposition would occur for particles larger than 15 μm. About 60% of the eroded mass is ≥ 15 μm, and so has the capacity to deposit upstream of the 4th Street turning basin. However, the settling rates for the finer particles of that mass (approximately 7% of the eroded mass) are low and so these particles may transport downstream before they can settle through the water column. As a result, the coarse, medium, and fine silts (representing another approximately 25 percent of the eroded mass) would form a graded deposit, slightly deeper and with larger particles diameters at the upstream end than at the downstream end. Overall, approximately 53 percent of the eroded mass will be deposit upstream of the 4th Avenue turning basin. The remaining 47 percent of eroded mass in the silt and clay size fractions would continue to be transported downstream as suspended load.

## *A Subjective Correction for Cohesive Sediment*

The previous transport assessment for non-cohesive particles assumes that the sediment mass scoured by the Flushing Tunnel turbulent jet disaggregates completely and transports as discrete constituent particles. As such, treating the scoured sediment as non-cohesive provides a limiting case where predicted transport is maximized. No suitable objective method exists for performing a similar assessment while treating the scoured sediment mass as cohesive. Subjectively, the expectation is that cohesive sediment scoured by the Flushing Tunnel would transport primarily as sediment aggregates moving as bed load. Much of this material would deposit in the Sackett Street depression (625 ft from canal head) and in a second depression further downstream near Union Street (900 ft from canal head, Figure 15 and Figure 18). Roughly 70 percent of the scoured mass would likely deposit within the upper 2,500 feet of Gowanus Canal. A finer fraction would continue downstream as suspended load, with another 20 percent of the scoured mass forming a graded deposit within the remaining length of the canal. Some 10 percent of the scoured mass may disaggregate completely to very-fine silt and clay-size particles. Particles in this size range are suspended easily by near-bed turbulence and settle very slowly due to gravity. It is conceivable that this finest fraction of scoured sediment might be transported into Gowanus Bay.

## CONCLUSIONS

Maximum discharge rates with the renovated Gowanus Canal Flushing Tunnel will be 40 percent greater than the pre-renovation maximum discharge rate. Results of a CFD modeling analysis, together with available bathymetry and grain-size characteristics of the sediments in the area, indicate that reactivation of the renovated Flushing Tunnel could scour approximately 27,000 $ft^3$ of Gowanus Canal sediments from a 6,500 $ft^2$ area in the vicinity of the tunnel outlet. A sediment-transport assessment treating the eroded sediment as non-cohesive indicates that about 53 percent of the scoured mass would deposit in the upper Gowanus Canal (within 2,500 ft of the canal head). However, a subjective assessment treating the eroded mass as cohesive contends that some 70 percent of the scoured mass would deposit within the same region. In either case, it is expected that some fraction of the finest grain-size material (up to perhaps 10 percent of the scoured mass) may transport as suspended load as far as Gowanus Bay.

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# FIGURES

**Figure 1.**
**Flushing Tunnel Route From Buttermilk Channel (at left) to Gowanus Canal (at right)**

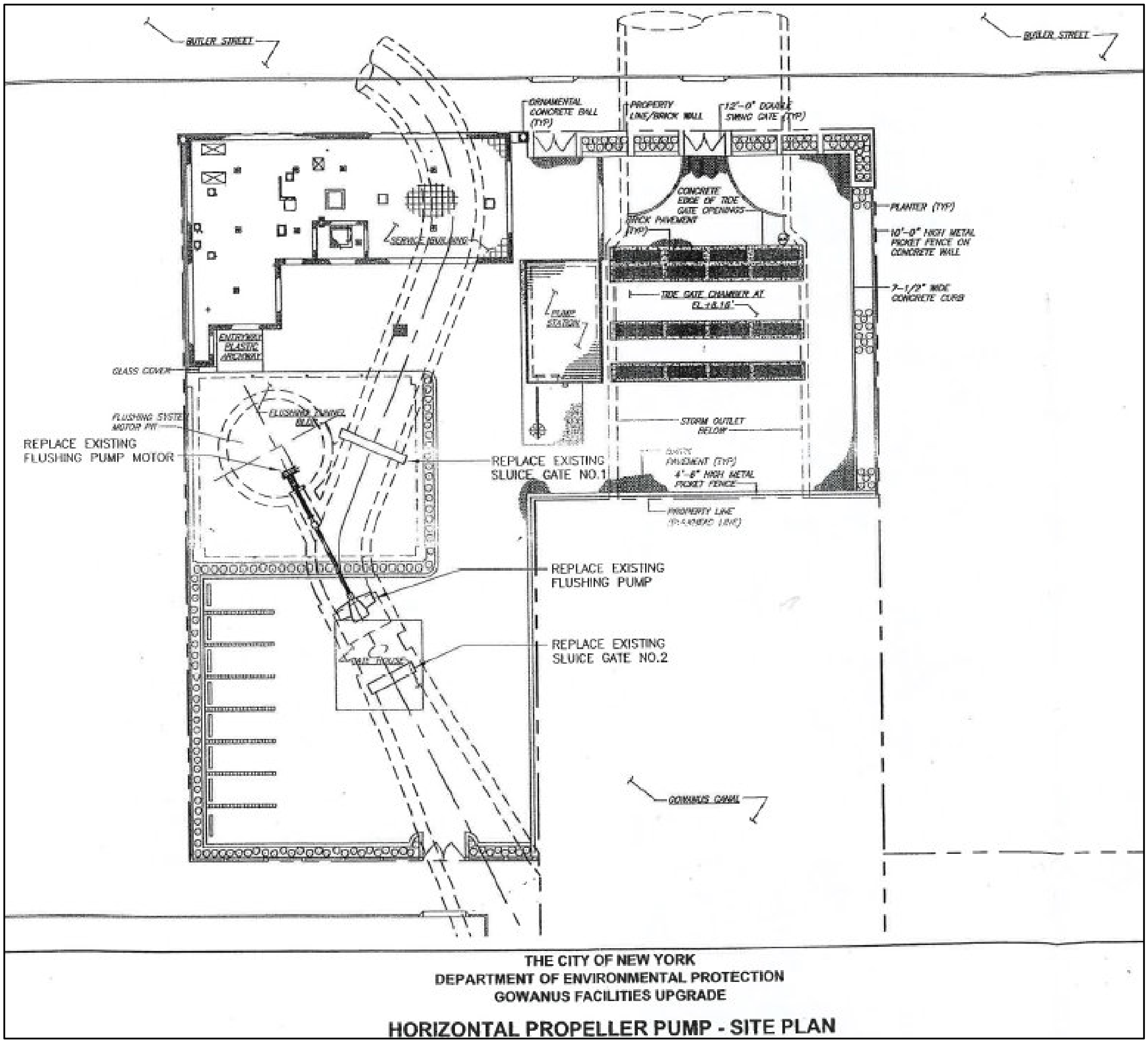



**Figure 2.**
**Flushing Tunnel Near Outlet to Gowanus Canal**

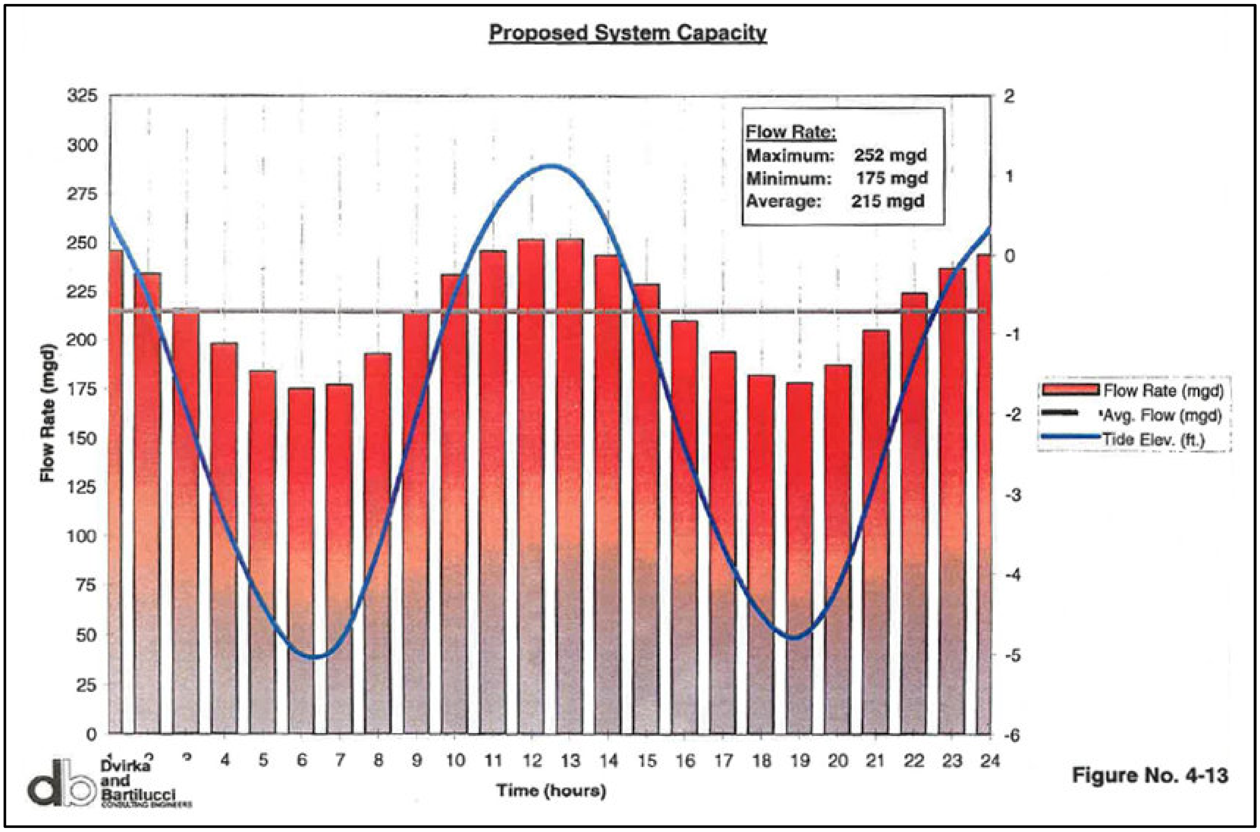
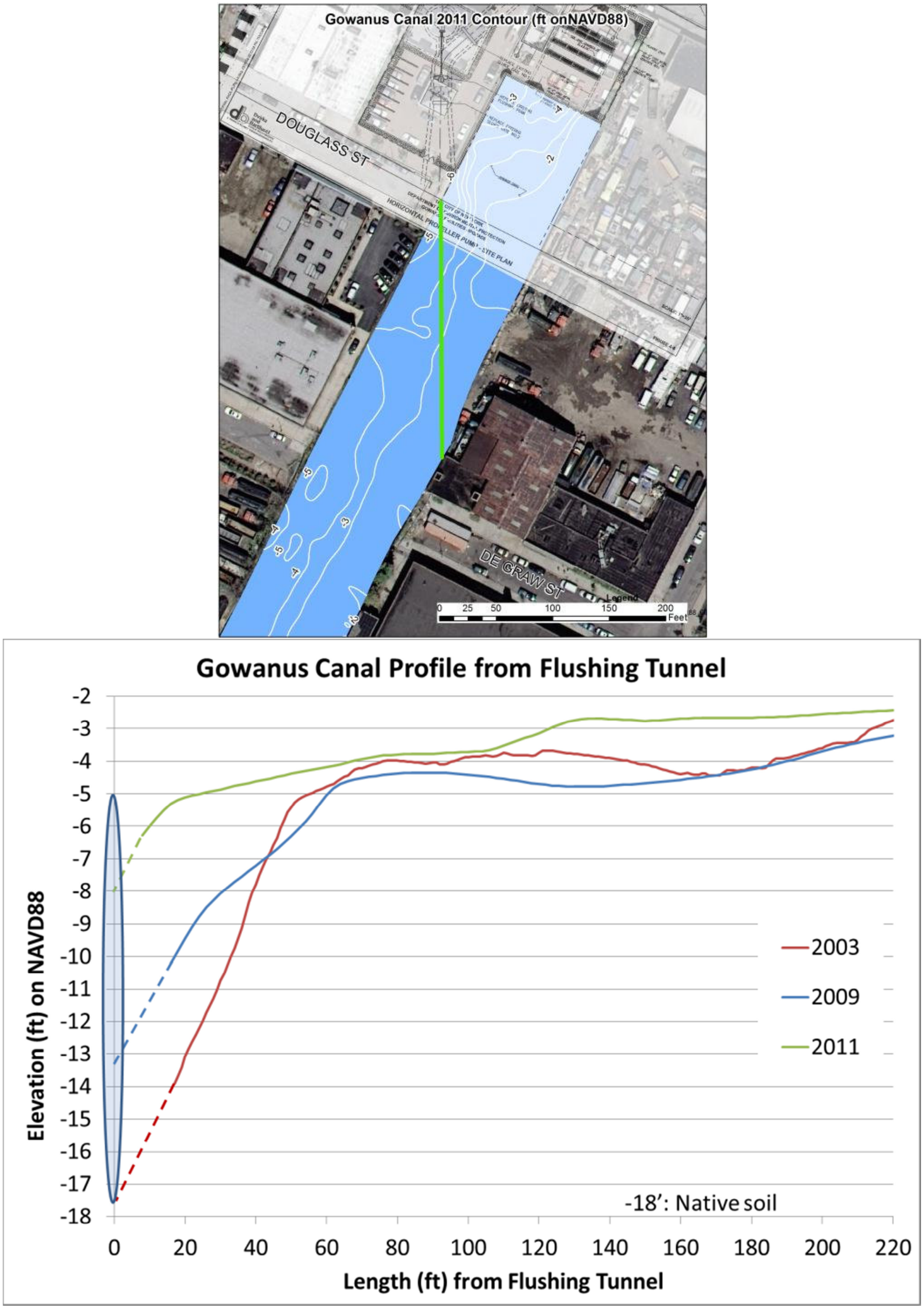
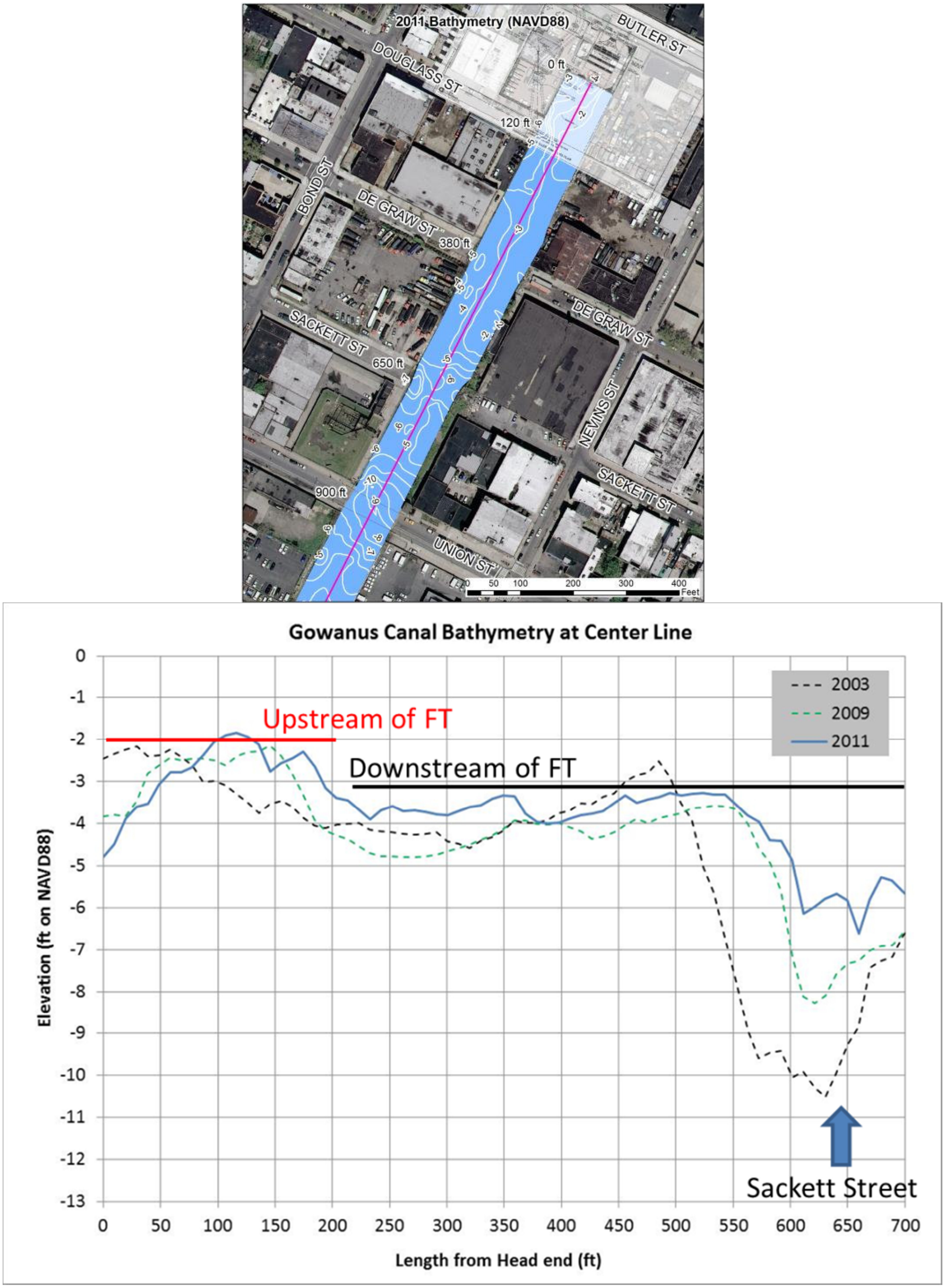



**Figure 3.**
**Renovated Flushing Tunnel Pumping Capacity**
**with respect to tidal elevation (Brooklyn Highway Datum).**



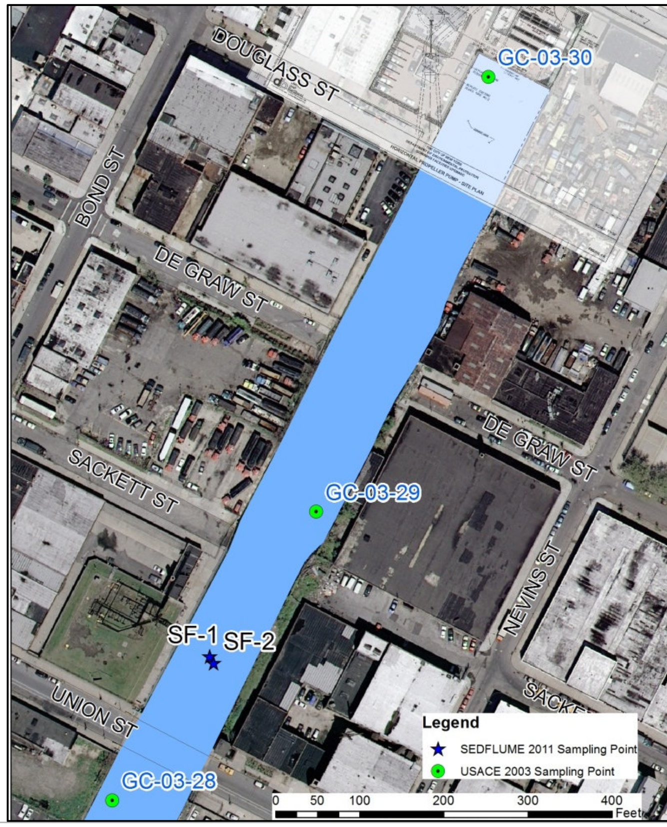

Note: lower-panel graphic shows bed profiles taken from green transect shown on upper-panel photo; Also, Flushing Tunnel shown schematically at left to provide reference depths for invert and crown.

**Figure 4.**
**Gowanus Canal Bathymetry Profile Near Flushing Tunnel Outlet, 2003, 2009, 2011**




Note: bed-elevation profiles on bottom-panel graphic taken from purple transect shown on top-panel photo

**Figure 5.**
**Upper Gowanus Canal Centerline Bathymetry, 2003, 2009, 2011**



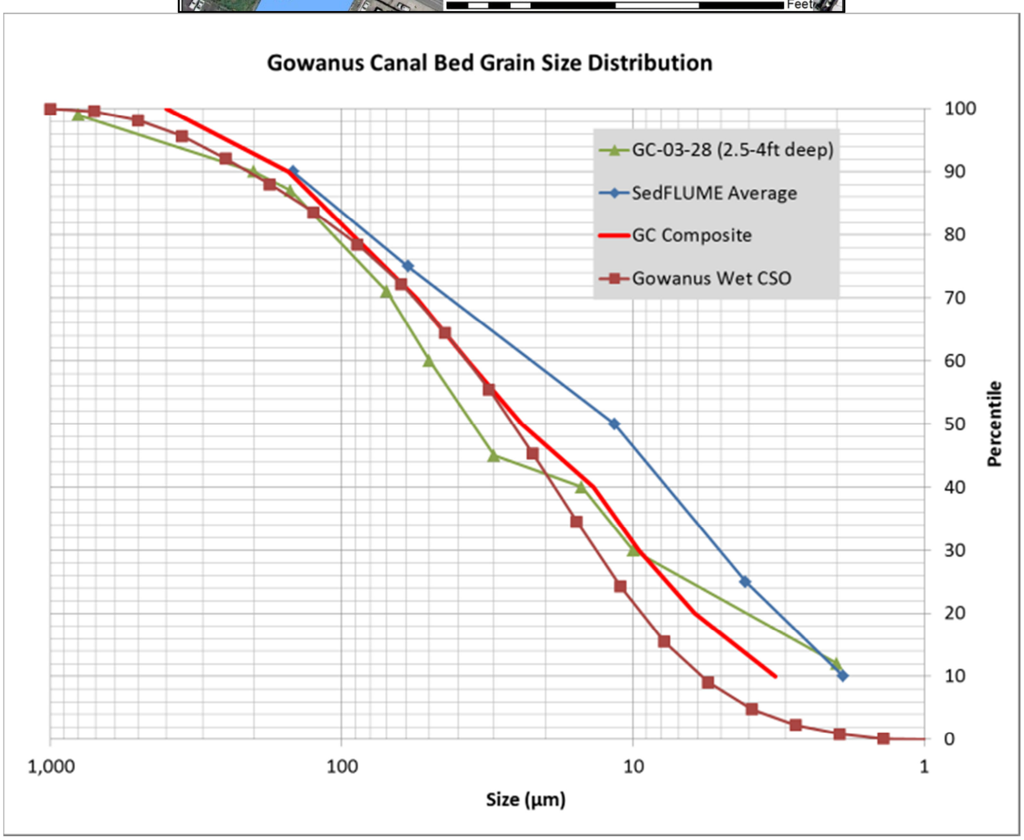




**Figure 6.**
**Grain Size Distributions for Gowanus Canal**
**(Sediment Cores, SedFlume Tests, CSO Solids, and Composite)**

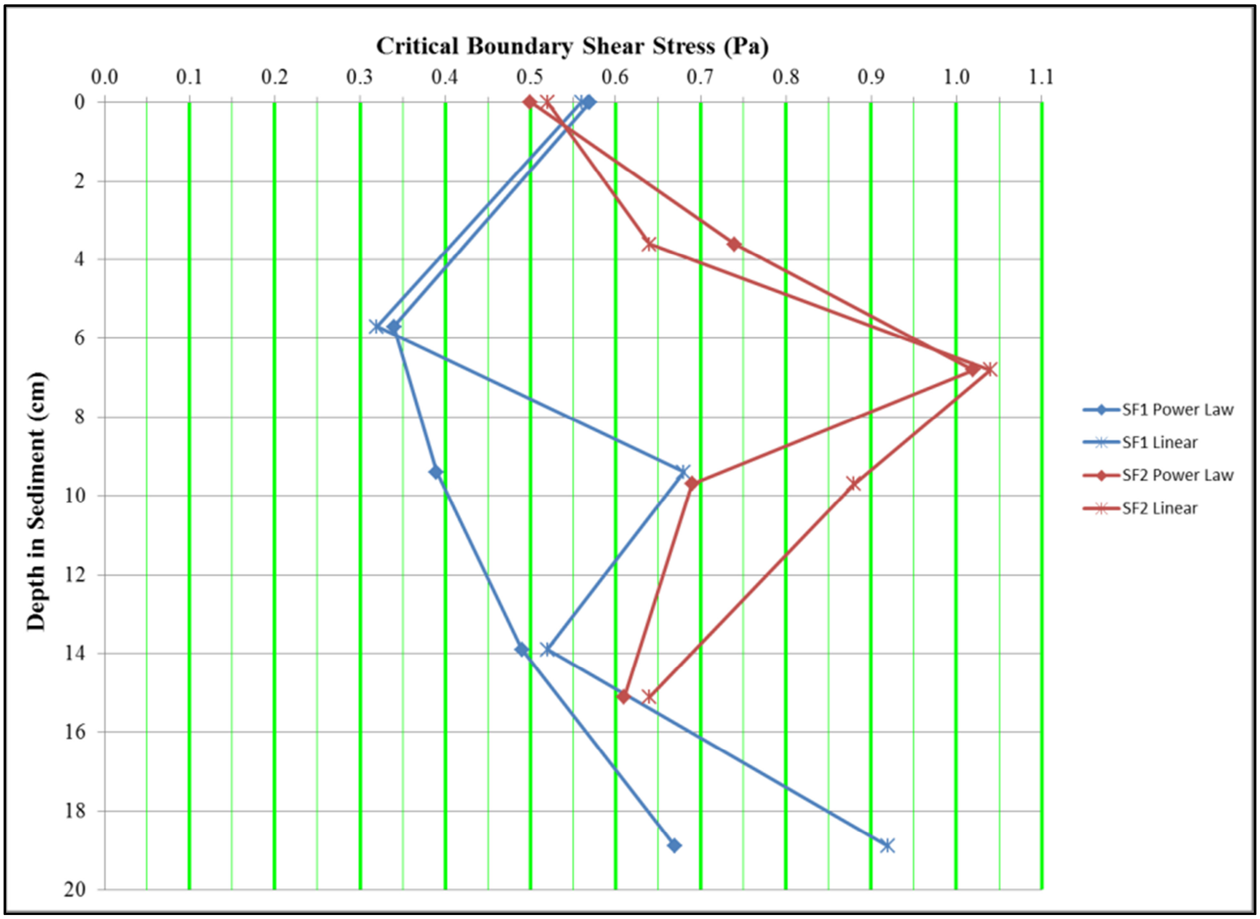



**Figure 7.**
**Critical Bed Shear Stress, Gowanus Canal Bed Samples**

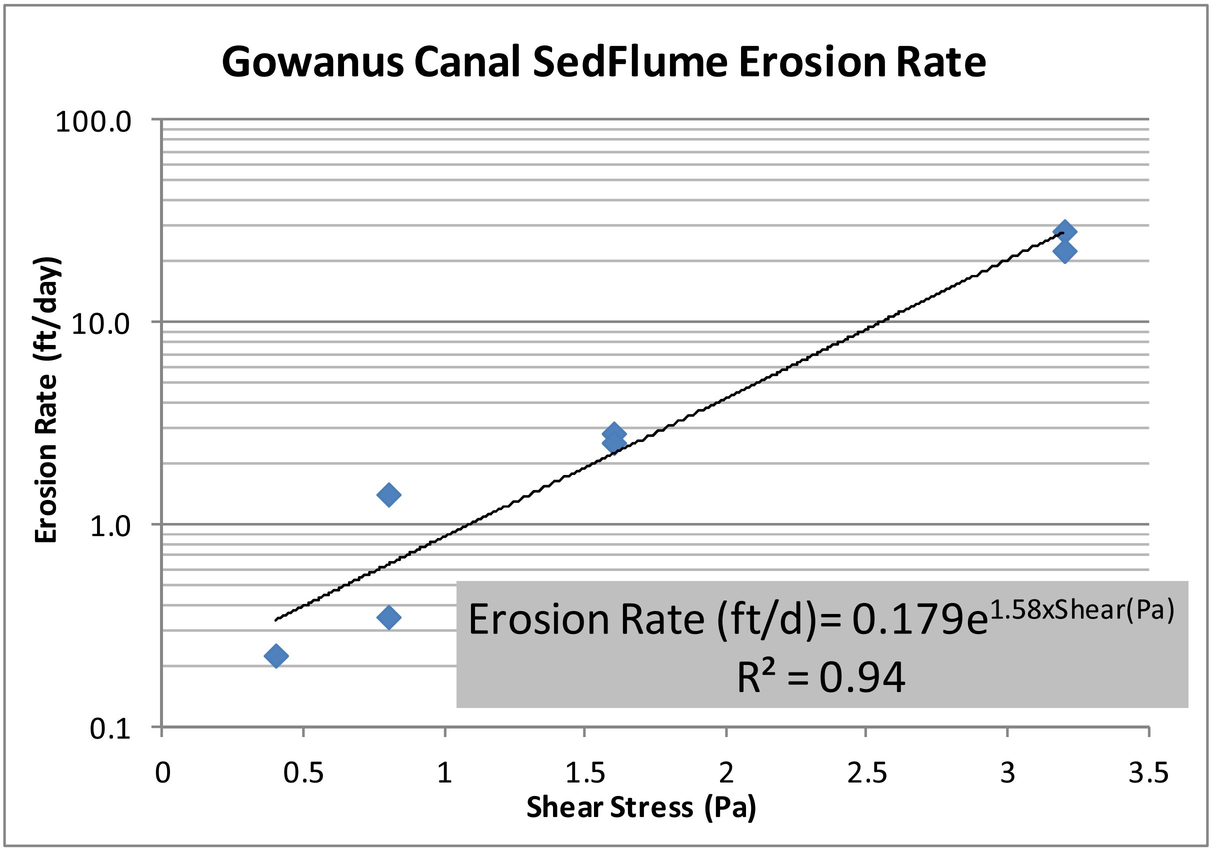
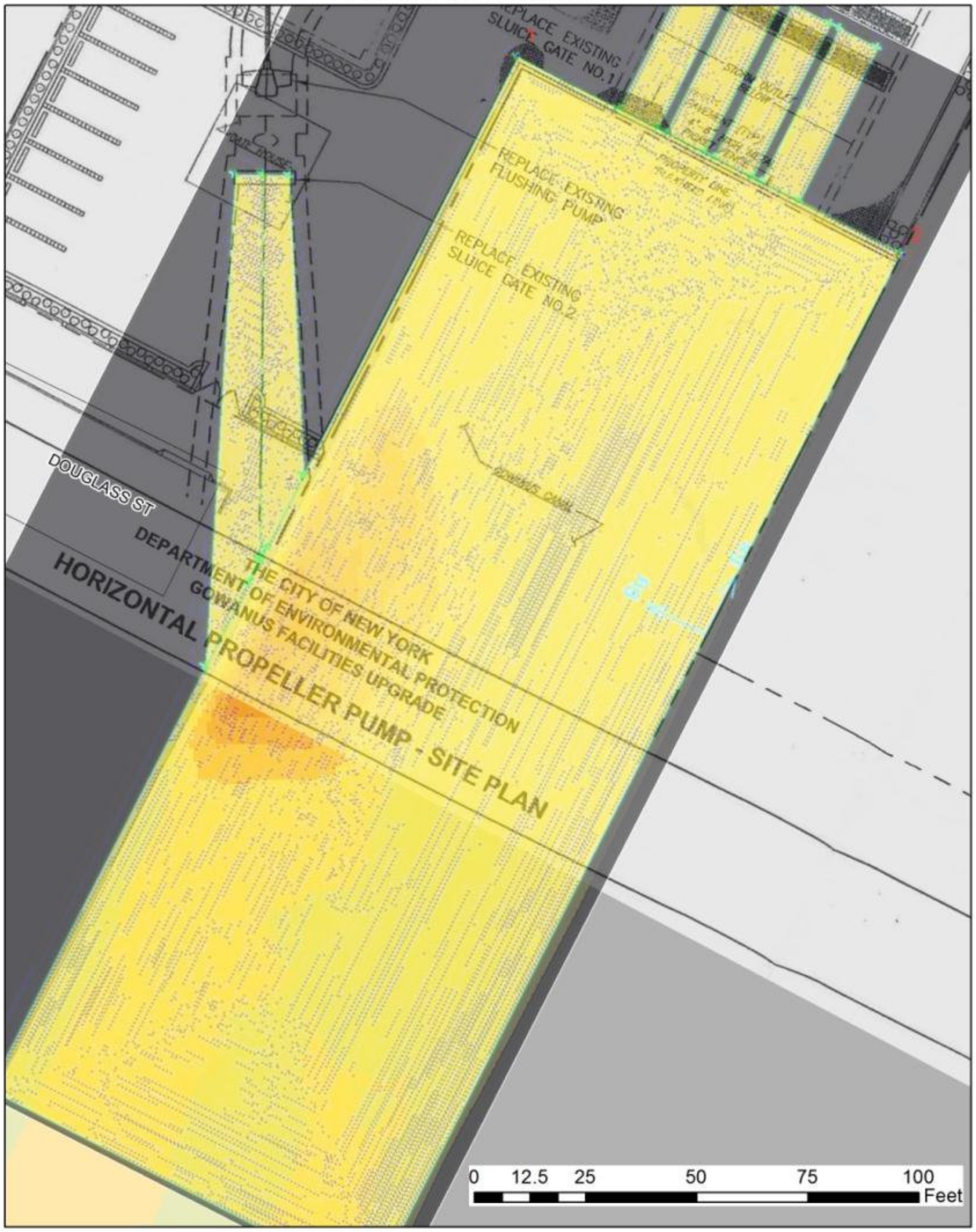



**Figure 8.**
**Observed Sedflume Erosion Rate**

CFD Model Domain




Note: Canal is 100 ft wide, domain extends 270 ft downstream (without expanded section, not shown). Individual cells measure approximately 0.7 ft by 0.7 ft by 0.7 ft.

**Figure 9.**
**Geometry of Gowanus Canal Flushing Tunnel CFD model**

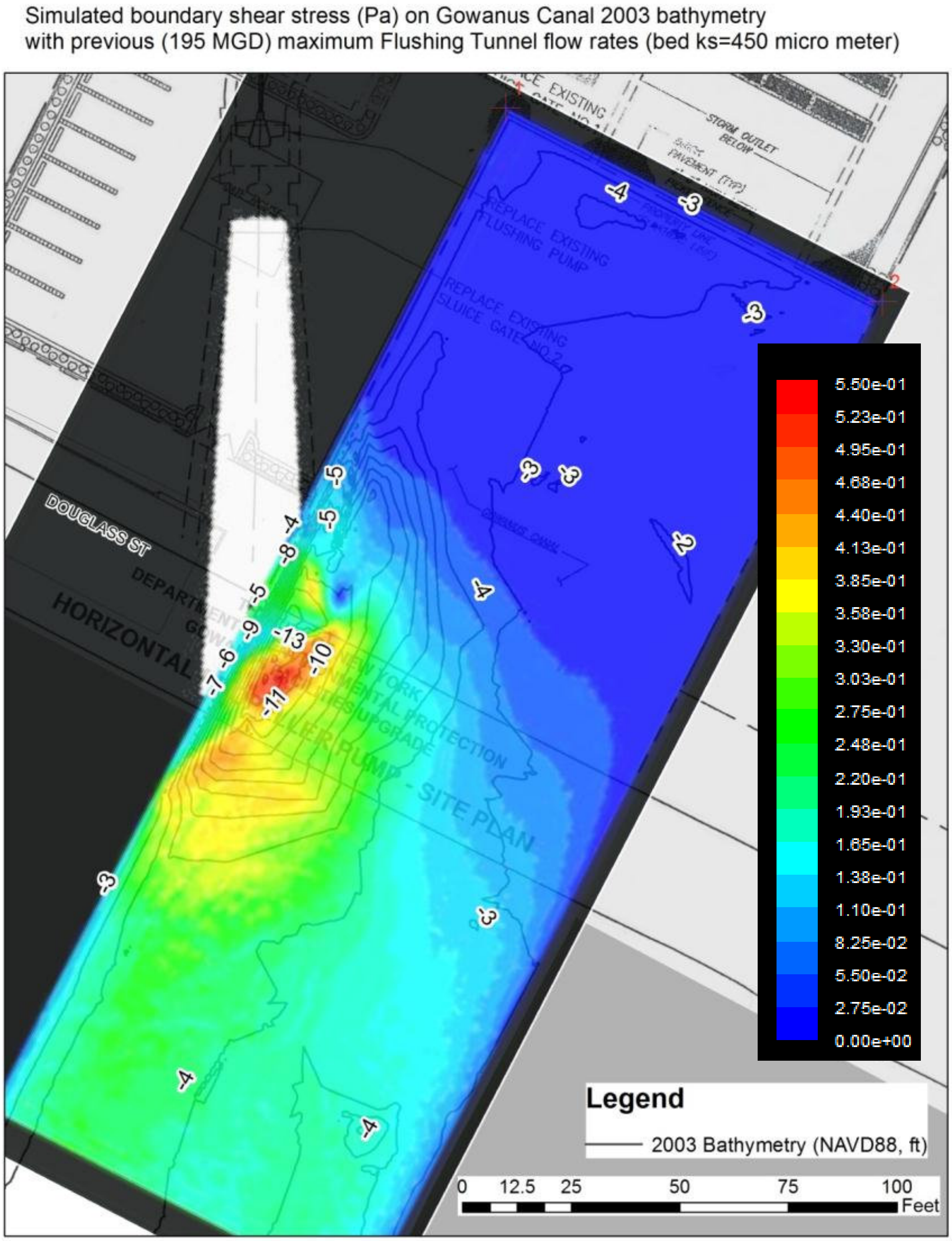



**Figure 10.**
**Model-Computed Bed Shear Stress (Pa) with 2003 Bathymetry, Pre-Renovation Flushing Tunnel Maximum Discharge Rate (195 MGD) and Calibrated Bed Roughness ($k_s$ =450 µm)**

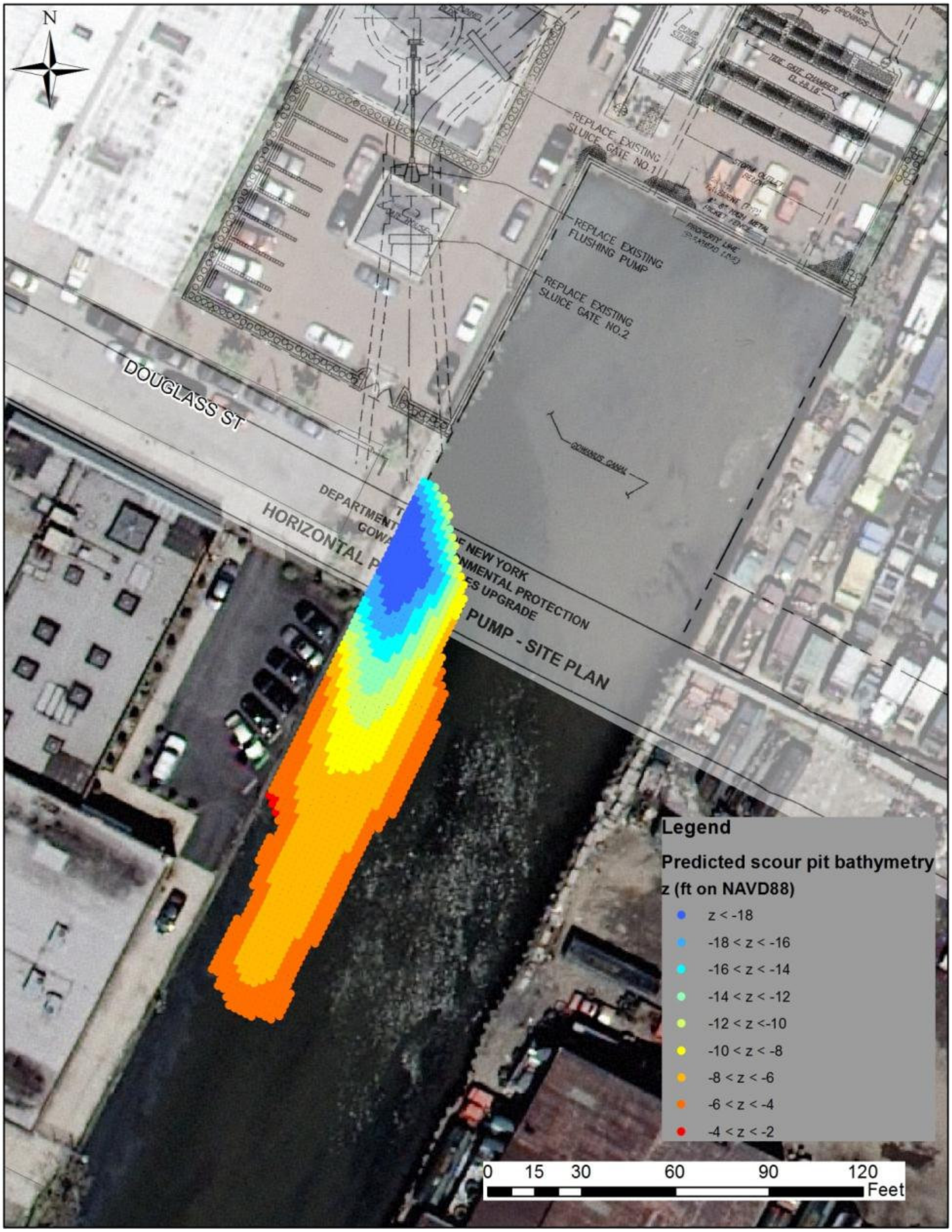



**Figure 11.**

**Predicted Scour-Furrow Bathymetry (NAVD88) with Post-Renovation Flushing Tunnel Maximum Discharge Rate (252 MGD) and Calibrated Bed Roughness ($k_s$ = 450 µm)**

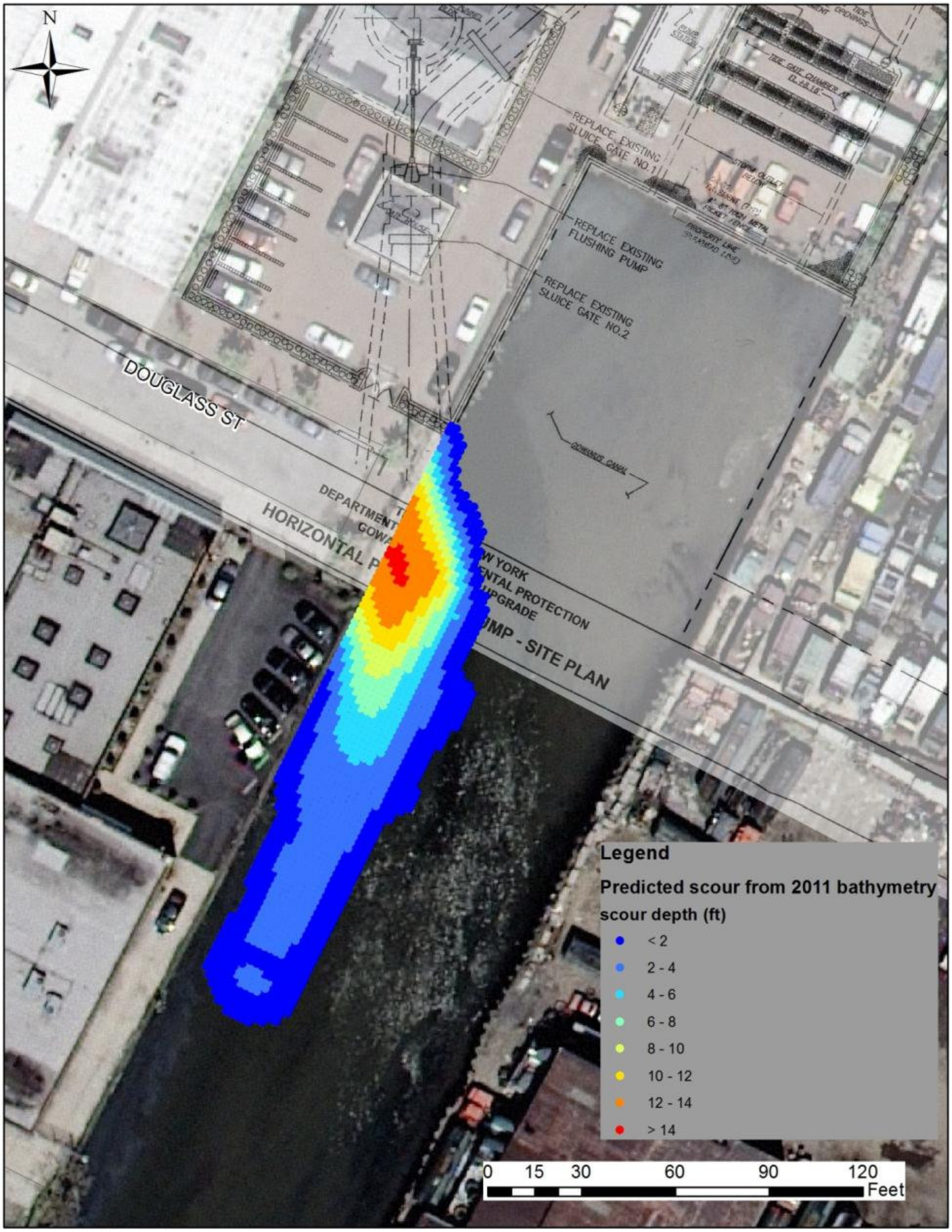
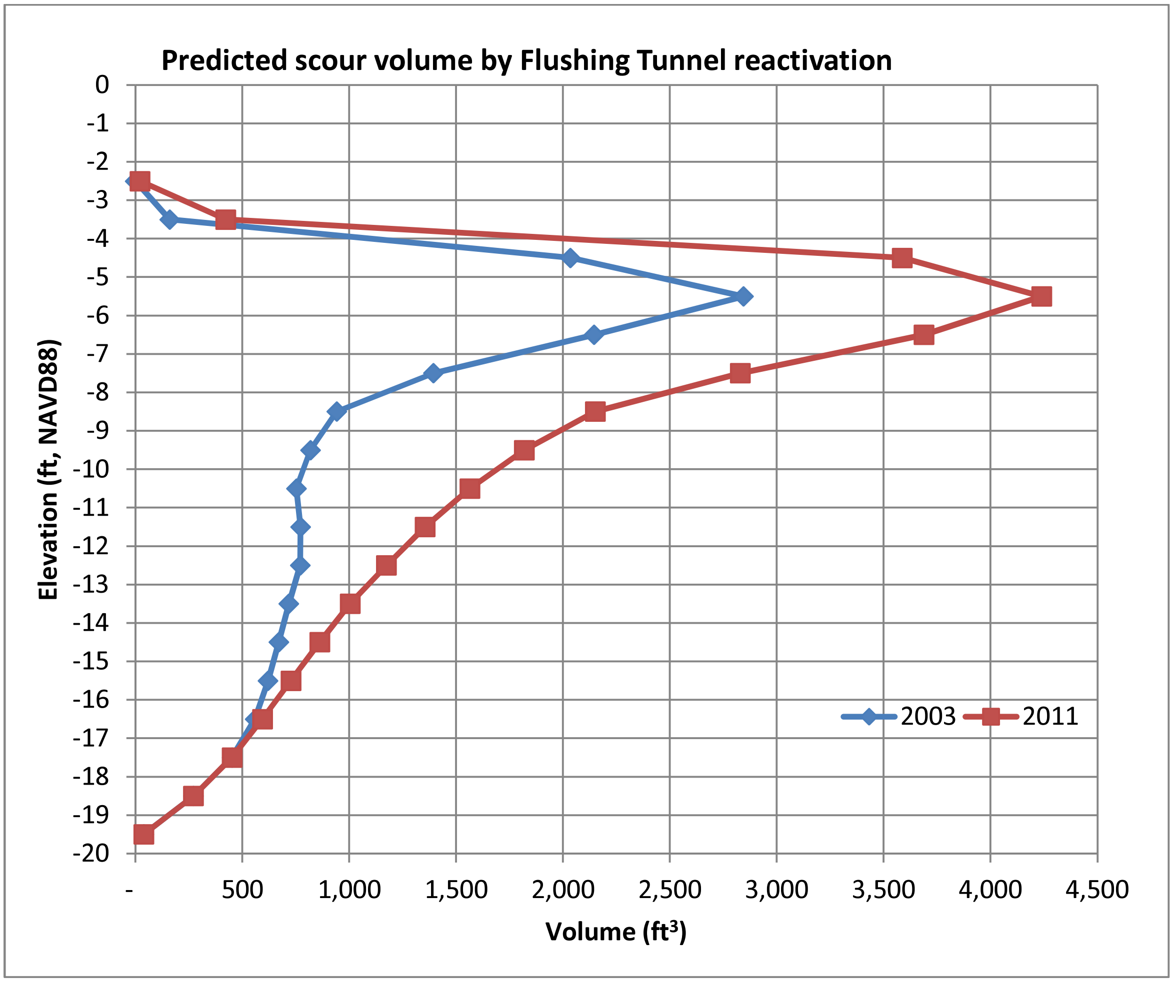



**Figure 12.**

**Predicted Depth of Scour (ft) Relative to 2011 Bathymetry, with Post-Renovation Flushing Tunnel Maximum Discharge Rate (252 MGD) and Calibrated Bed Roughness ($k_s$= 450 µm)**




Note: total scoured volume in each 1-ft horizontal layer removed assuming 2011 initial sediment profile shown in red as "2011" (total: 27,000 cf); incremental volumes below 2003 sediment profile shown in blue as "2003."

**Figure 13.**
**Calculated Sediment Scour Volume for Post-Renovated Flushing Tunnel Maximum Discharge Rate (252 MGD) when starting with 2011 Sediment Profile**


**Figure 14.**
**Three Transects (West, Center, East) Used To Estimate Average Lateral Depth**

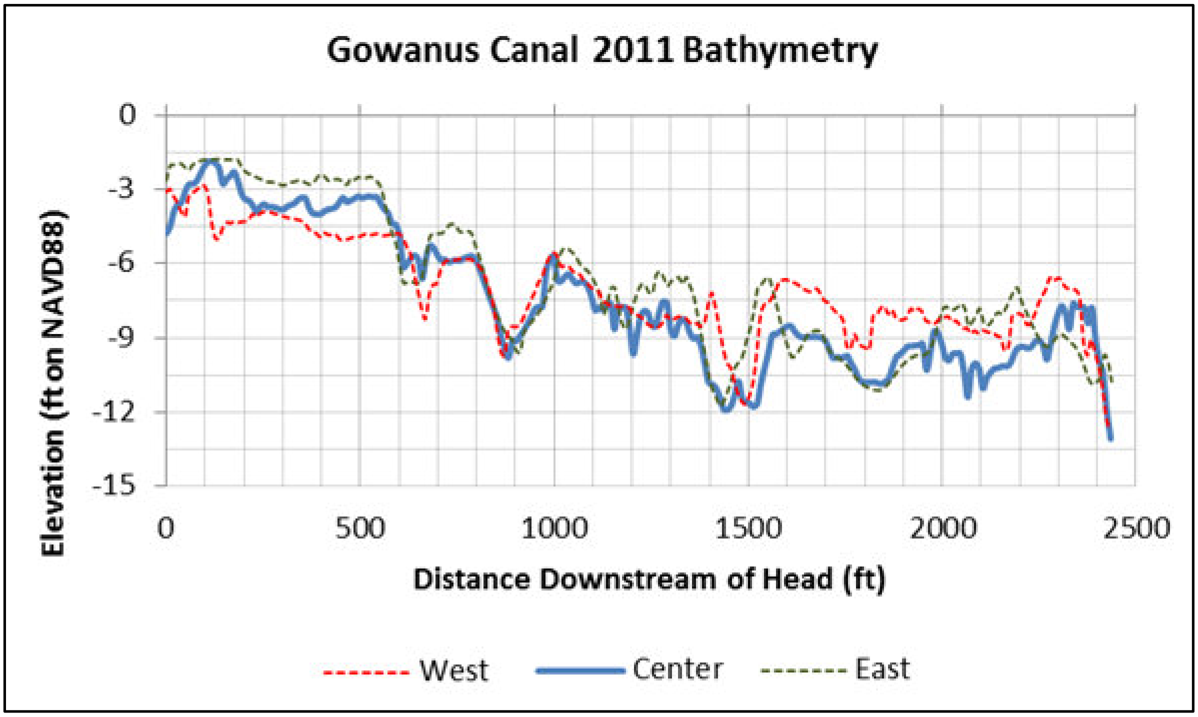



**Figure 15.**
**Gowanus Canal 2011 Bathymetry Along Three Axial Transects**

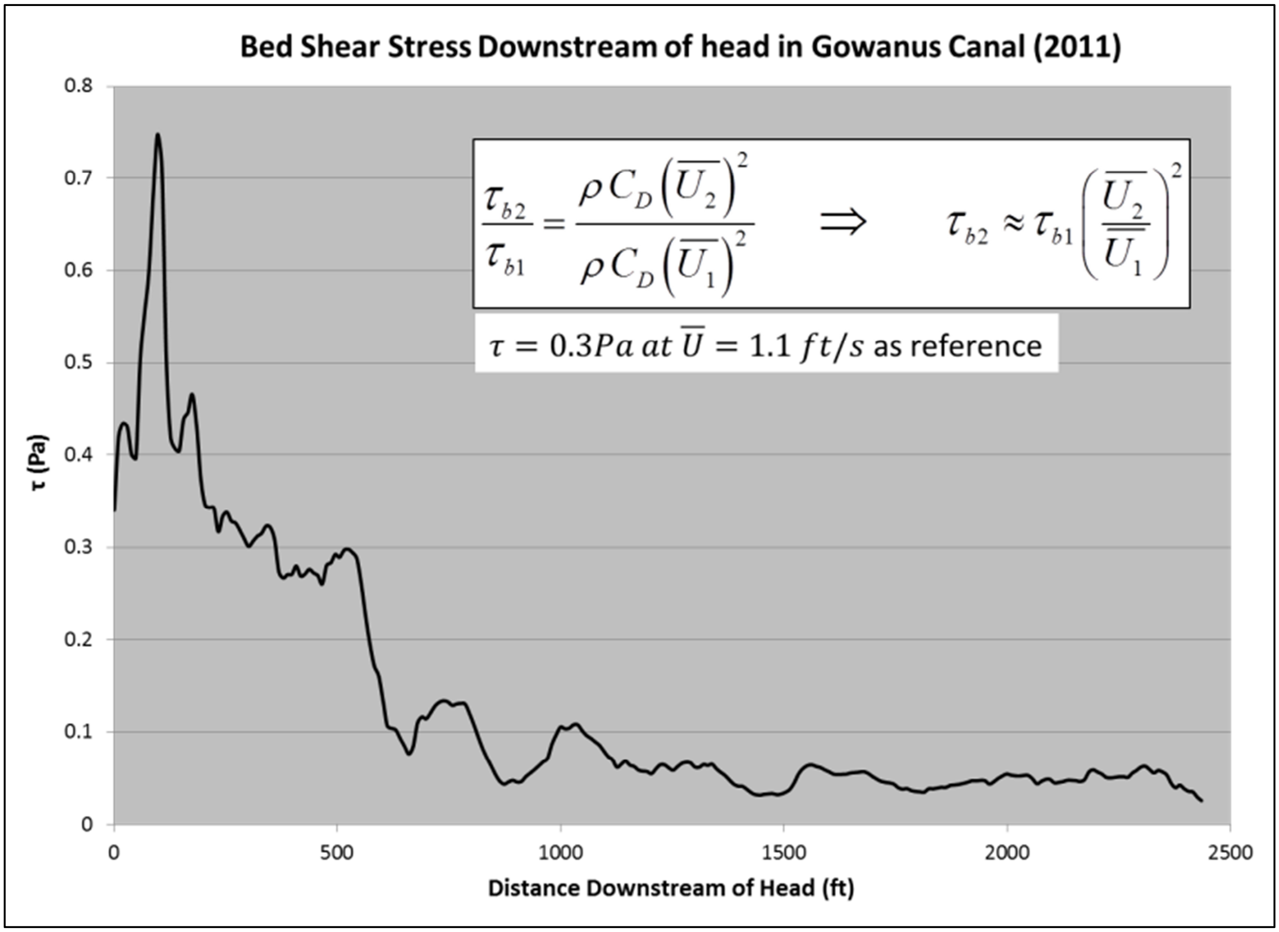



**Figure 16.**
**Calculated Bed Shear Stress in Gowanus Canal**

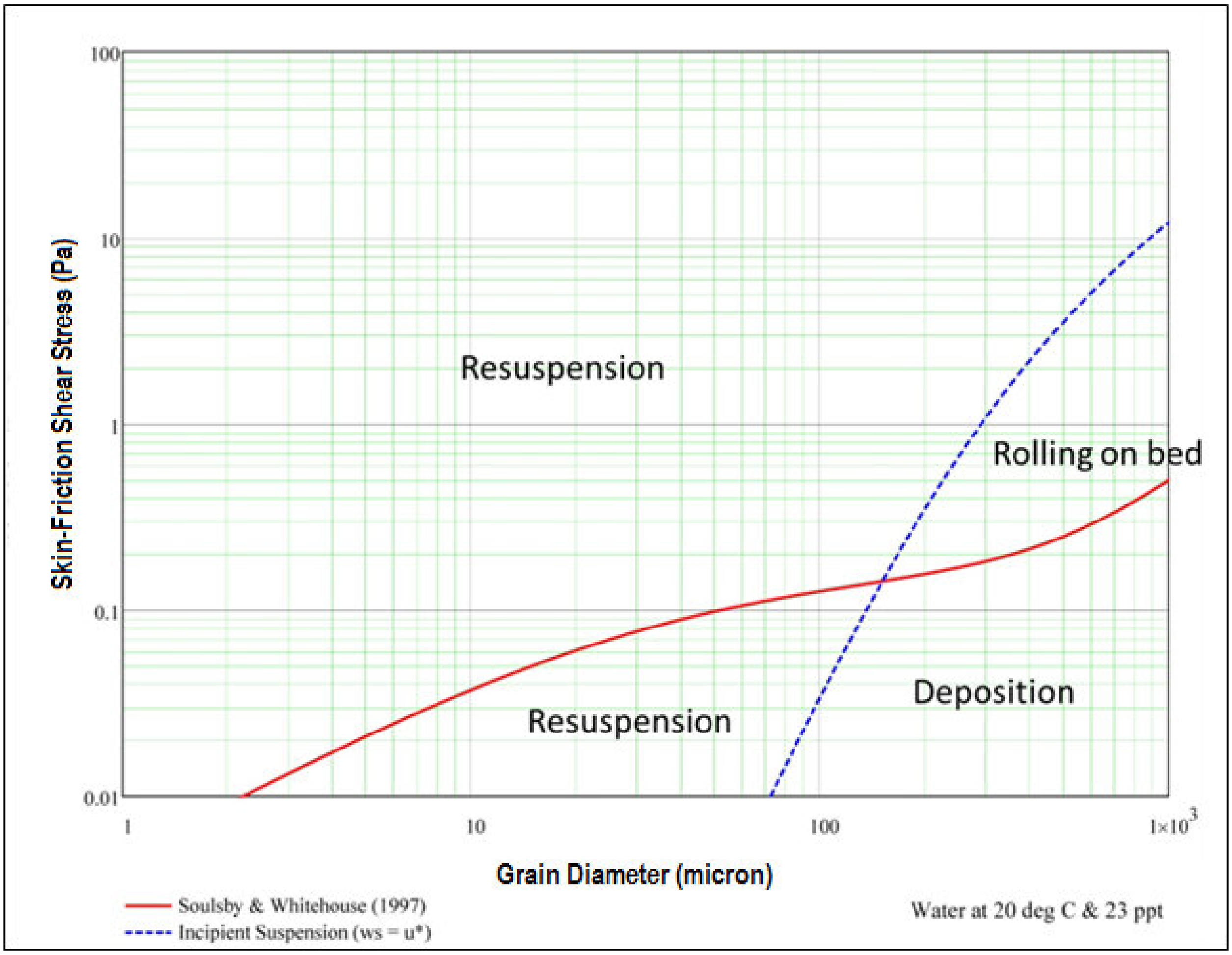
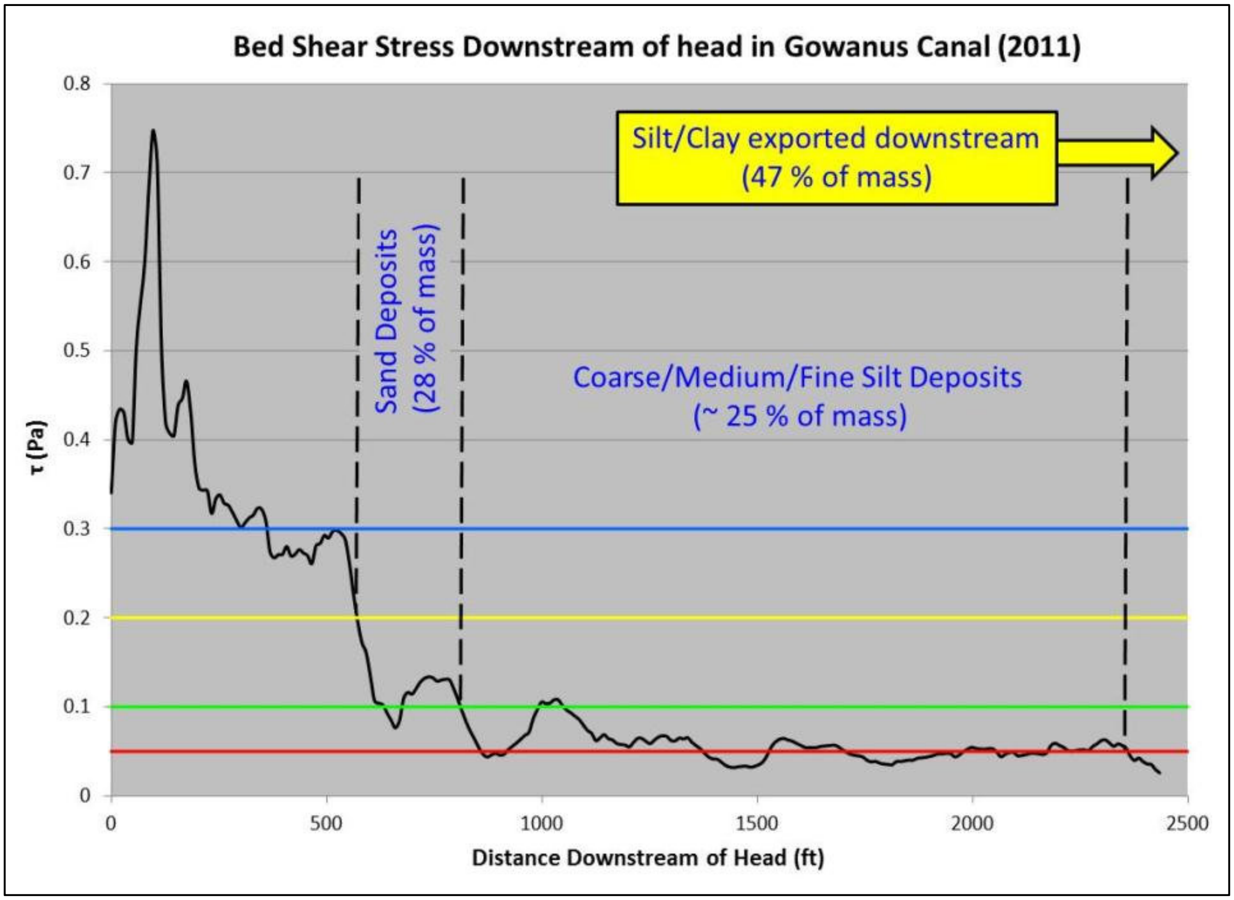



**Figure 17.**
**Particle Depositional Behavior Depending on Shear Stress and Particle Size**




Note: Schematic represents results of a screening-level analysis of non-cohesive particle settling of the sediment scoured by the renovated Flushing Tunnel in the Upper Gowanus Canal with 2011 Bathymetry

**Figure 18.**
**Predicted Deposition Of Scoured Sediment**